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WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification⁶:

B01J 21/06, 23/06

A1

(11) International Publication Number:

WO 95/11751

(43) International Publication Date:

4 May 1995 (04.05.95)

(21) International Application Number: PCT/US94/12185

(22) International Filing Date: 21 October 1994 (21.10.94)

(30) Priority Data:

08/143,286	26 October 1993 (26.10.93)	US
08/143,301	26 October 1993 (26.10.93)	US
08/216,731	22 March 1994 (22.03.94)	US

(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published

With international search report.

after
3/20/95

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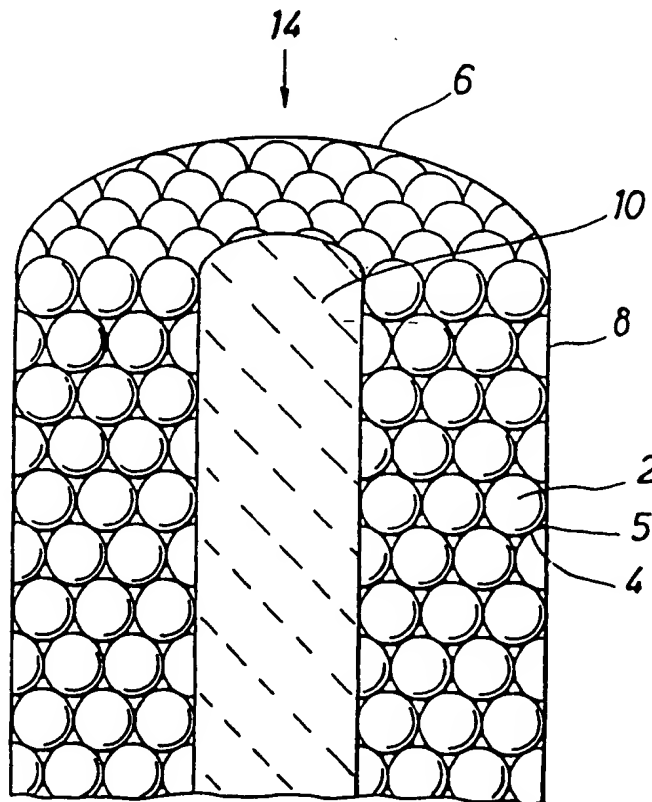
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(54) Title: PHOTOCATALYST-BINDER COMPOSITIONS

(57) Abstract

A photocatalytic composition containing a substantially non-oxidizable binder, such as silicone, which allows large amounts of photocatalytic particles, such as titanium dioxide or zinc oxide, to be adhered to a surface. Upon application to a surface, the composition dries or cures to form an adherent, abrasion-resistant, thermostable photocatalytic coating. The binder transmits a substantial proportion of incident ultraviolet light to activate the photocatalytic particles to produce a cleaning effect. The binder, preferably polysilicone, renders the surface hydrophobic. The coated surface can be used to degrade organic contaminants in air or in an aqueous stream, and can act as a biocidal agent under the application of ultraviolet light. When an organic reaction is to be catalyzed under the ultraviolet light, such coated particulate materials can be used as photocatalysts in a fluidized bed reactor, or a packed bed reactor. The photocatalytic composition is used in a photoreactor (14) containing a packed bed (6) packed with glass spheres (2), optionally with a silicone coating only at the points of contact (4), within a conduit (8) which surrounds a source of ultraviolet light (10). Preferably a silicone film (12) is placed between the conduit (8) and the glass spheres.



TITLE: PHOTOCATALYST-BINDER COMPOSITIONS

RELATED APPLICATIONS:

This invention is a continuation-in-part of copending U.S. patent application number 08/216,731 filed March 22, 1994; which is a continuation-in-part of 08/143,286 and 08/143,301, both filed October 26, 1993; which are continuations-in-part of PCT/US92/01790 which was filed on March 5, 1992 and entered the U.S. National Stage on April 18, 1994 as U.S. Patent Application No. 08/244,149; which is a continuation-in-part of U.S. Patent No. 5,256,616 issued October 16, 1993. Each of these patents and patent applications are hereby incorporated by reference for all purposes.

FIELD OF THE INVENTION:

This invention relates to compositions containing a photocatalyst and novel binders and to methods of using such compositions. The binders permit the photocatalyst to adhere to a surface without loss of chemical reactivity of photocatalyst. In addition, the composition of the invention does not exhibit damage to the binder or to the underlying surface upon exposure to light absorbed by the photocatalyst. In a preferred embodiment, a hydrophobic and oxygen permeable binder or added hydrophobic and oxygen permeable overcoating enhances photocatalytic activity.

BACKGROUND OF THE INVENTION:

Heterogeneous photocatalysis has shown promise as a chemical method for oxidizing and thereby removing unwanted organic compounds from fluids, including water, and air. A UV-illuminated catalyst, such as titanium dioxide, absorbs UV light, which produces electrons and holes that migrate to the surface of the catalyst. At the surface,

the electrons reduce adsorbed oxygen, while the holes oxidize organic compounds or adsorbed water molecules.

For example, titanium dioxide is a semiconductor with a band gap of 3.0 eV (rutile) and 3.2 eV (anatase). When a photon having an energy in excess of the band gap is absorbed by the pigment particle, an electron is promoted from the valence band to the conduction band. The promotion of the electron produces a "hole." The hole and the electron may diffuse to the surface of the pigment particle where each may chemically react. Surface electrons generally reduce adsorbed oxygen, while surface holes generally oxidize organic compounds or adsorbed water molecules. When electron vacancies (holes) react with water, reactive OH radicals and protons are formed.

In related U.S. Patent No. 5,256,616 and related U.S. Patent Application No. 08/244,149, ceramic beads coated with titanium dioxide efficiently induced the oxidation of oil on water when exposed to natural sunlight. Others have also utilized photocatalytic reactions to remove contaminants from air and water. See, for example, U.S. Patent No. 5,045,288 to Raupp et.al.; PCT Patent Application No. PCT/US90/07651 to Lichtin et al. published July 11, 1991; Japanese Kokai Patent Application No. Sho63[1988]-100042 to Kume, published May 2, 1988; and Australian Patent Application No. PH7074, July 22, 1987 of Matthews.

While the use of photocatalysts for the removal of organic pollutants is generally known, a commercially feasible process for the use of such catalysts has not been developed. Known methods for adhering the photocatalyst to a reactive surface such as heat sintering have been impractical or too expensive to apply to very large surface areas such as those for air cleaning or the production of large areas of self-cleaning surfaces. In a fluid reactor, e.g., for air or water, a large photocatalytic surface area

in contact with the air or water to be cleaned is advantageous. In prior art methods of bonding the photocatalyst to a surface, such as sintering, the actual catalyst surface area per unit geometric area was reduced.

5 Consequently, reactors functioning at a given flow rate, required large catalyst-coated surface areas. This not only increased the required size of the reactor, but also created a large pressure drop in the reactor, making the reactor expensive to operate. Because rates of removal of
10 contaminants from air or water in a reactor have been too low to justify the high costs involved and photocatalytic air or water cleaning and reactors have not been introduced for general use, i.e., for cleaning air in office buildings, homes, restaurants or factories, or for cleaning
15 water in homes or municipal water plants.

The photocatalyst compositions of the prior art are not easily applied to substrates; and especially to those having a large geometric surface area such as walls, windows and the like. Typically, such compositions are
20 generally applied as an aqueous slurry, and are poured, sprayed, dipped, or otherwise coated onto a substrate as a thin film. The photocatalyst is adhered to the substrate by heat sintering or calcifying. To gain any thickness of the photocatalyst film, the process must be repeated many
25 times.

When pigments such as titanium oxide (TiO_2) are used in paints, hydrocarbon binders such as latex or polyurethane are generally used to adhere the pigment particles to each other and to a surface. Since photocatalytic activity of
30 the pigment particles has been considered undesirable in paint, e.g., due to destruction of the hydrocarbon binders and the like, considerable effort is made to prevent it. This is because the oxidative reactions of the photocatalyst in the presence of sunlight and air degrade

the polymeric hydrocarbon binder and causes undesirable "chalking" of the paint.

To mask the activities of the photocatalyst, the TiO_2 pigment particles in paints are generally enveloped or coated with a nonporous composition containing aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), or both. These include, for example, TiO_2 pigments available from Kronos, Inc., Houston, Texas as catalog numbers 1000, 1070, 1072, and 1074; Lansco 8042 from Landers Segal Color Co., Passaic, New Jersey. This overcoating prevents diffusion of electrons or holes to the pigment surface thereby preventing contact and reaction with the polymeric binder, e.g., latex or polyurethane, or with water or oxygen. Essentially all of the TiO_2 pigment used today in the manufacture of paints is rendered less photoactive by overcoating with aluminum oxide, silicon dioxide, or both. While this overcoating permits application of the pigment to a surface and preserves the appearance of a painted surface, it precludes photocatalytic reactions desired to remove contaminants from a surface, air or water.

To solve these problems and to produce a photocatalyst-binder composition useful in a variety of applications, it has surprisingly been found that photocatalyst particles adhere to a substrate by the use of substantially non-oxidizable binders. Being permeable to the organic contaminant-reactant and to oxygen, as well as their reaction products, carbon dioxide and water, such binders do not impede, and can even enhance, photocatalytic activity.

30 SUMMARY OF THE INVENTION:

The invention provides a photocatalytic composition including a photocatalyst and a binder for adhering the photocatalyst particles to a surface. The binder permits application and adherence of the photocatalyst to a variety

of surfaces without significantly impeding or blocking the activity of the photocatalyst. In some instances, the binder can even enhance photocatalytic activity. The binder of the photocatalytic composition is not degraded and its appearance is not altered by the activity of the photocatalyst.

The binder can be thermosetting as defined, *infra*, on page 7. When a dispersion of the photocatalyst and binder is applied to a surface, the composition dries and/or cures to form an abrasion-resistant, stable composition which adheres to most any surface, including metal, glass, plastic, wood, fiber and painted surfaces.

The dried and/or cured binder composition, in the absence of photocatalyst, transmits ultra-violet (UV) light. In the presence of a UV-absorbing photocatalyst, the transmitted UV-light is absorbed by the catalyst, and is thereby prevented from reaching an underlying surface.

UV-induced photocatalytic reaction gradually oxidizes the composition but, upon complete oxidation of the binder, the photocatalytic composition of the invention remains adhered to a surface through the binder or its oxidation product, and is present on the surface as a transparent, non-volatile film.

The binders of the present invention permit the photocatalytic composition to adhere to a geometric surface without heating. Thus surfaces that previously could not be coated by sintering methods because of a necessary heating step, such as plastics and fibers, may now be coated with the inventive photocatalyst-binder composition.

The binders of the present invention have a high Brunauer-Emmett-Teller (BET) surface area resulting from permeability of the binder and/or microporosity of the composition.

In a preferred embodiment, the photocatalyst useful in the invention is selected from the group consisting of photoactive transition metal oxides, including, but not limited to TiO_2 , ZnO , WO_3 , SnO_2 , CaTiO_3 , Fe_2O_3 , MoO_3 , NbO_3 , $\text{Ti}_x\text{Zr}_{(1-x)}\text{O}_2$, and to silicon carbide, SiC . In the preferred
5 embodiments, the binder composition is formed of substantially permeable and UV-transmitting silicone, porous alumina or silica, boron oxide, silicone, or mixtures thereof.

10 Further, according to the present invention, the photocatalyst composition is employed to remove contaminants from air and water, as well as to remove undesirable organic material contacting a surface area such
15 as a wall, window, flooring, automobile exterior, boat surface, and the like. In a preferred embodiment, the photocatalyst composition of the present invention is
4.36 — incorporated onto or in conjunction with a particle filtering device for removal of particulate contaminants from an air or water stream passing through the device.

20 BRIEF DESCRIPTION OF THE FIGURES

Fig. 1 is a diagrammatic sketch of a wave-guiding packed bed photoreactor, shown partially in cross-section.

Fig. 2 is a diagrammatic sketch of a section of the packed bed reactor of Figure 1, showing possible paths of
25 reflected and transmitted UV light in the beads of the reactor.

DETAILED DESCRIPTION OF THE INVENTION

When used herein, the following definitions define the stated term:

30 "Thermosetting" means the ability of the fluid or deformable composition to be dried, hardened, or cured by removal of liquid, including at ambient temperature or by use of traditional curing agents including heat and UV

radiation, or by polymerization and crosslinking agents, or by a combination of these.

"Abrasion resistant" means the ability of the dried or cured composition not to be easily scratched or flaked away from a surface. Abrasion resistance is measured, for example, in the paint industry, by a scratch hardness test. This test is described in: Paint and Surface Coating: Theory and Practice, R. Lambourne ed, 1987, John Wiley and Sons, NY, p. 674-5. In its simplest form, this test uses a range of pencils having varying carbon hardness values, e.g., the softest pencil is a No. 1 ranging to a No. 4 as a harder pencil carbon. The coated surface is rubbed or written with each pencil. The abrasion-resistance value given to each surface can be defined as the maximum carbon hardness value, e.g. Pencil No., which runs across the surface without breaking the film or coating or can be defined as the softest pencil that will break the surface. Herein, the latter is used, e.g., the abrasion-resistance value is the number of the hardest pencil which does not break the coating. In the present invention, the preferred abrasion resistance value of the photocatalytic composition is at least 2, and is generally in the range of 2-3.

"Adherence" to a surface means the ability to be retained on the surface and may be tested, for example, by the "tape test." A piece of cellophane tape is adhered to the dried or cured composition and then removed. The compositions of the present invention will not be significantly pulled off the surface to which they has been applied, e.g., by the tape test.

"Thermostable" means the dried or cured compositions of the present invention will not be appreciably altered by normal changes in ambient temperatures, e.g., in the approximate range of 0°C to 50°C. The temperature range at which the photocatalytic compositions will be active extends at least from about 0°C to about 150°C.

The phrase "transmits ultraviolet light" means that the binder (in the absence of photocatalyst) when dried or cured and when illuminated with a source of ultraviolet light, is capable of transmitting through its thickness at least about 50% of the normally incident and non-reflected 340-380 nm photon flux, when the thickness of the neat binder layer is about 1 μ m. The preferred binders transmit at least about 50% of this same photon flux through a 10 μ m thick layer of the neat binder. With the addition of UV-absorbing photocatalyst, however, the cured and dried photocatalyst composition reduces the flux at the wavelength exciting the photocatalyst by about a factor of two or more, to the underlying surface, as the UV light is absorbed by the photocatalyst.

The term "substantially non-oxidizable" means the binders of the present invention have a backbone structure containing few oxidizable atoms. Preferably, the binders of the present invention have a backbone sequence of about 12 or more atoms, where no more than one in 6 atoms, and more preferably no more than 1 in 12 atoms is a carbon atom. The preferred binders do, however, contain oxidizable carbon and/or hydrogen atoms covalently bound to the backbone atoms.

The photocatalytic compositions of the present invention include a photocatalyst dispersed within a binder that can be thermosetting and which is substantially non-oxidizable after curing. The binder or binder precursor may be a polymerizable precursor, a non-crosslinked polymer, or a crosslinked polymer, provided the photocatalyst can be co-dispersed with the binder, and be easily spread over a geometric surface, i.e., a surface area to be coated with the catalyst. Note that the actual surface area, e.g., the area of the active photocatalyst in contact with fluid to be cleaned, may be much larger than

the geographic surface area because of the three-dimensional nature of the photocatalyst-binder matrix.

The photocatalytic composition preferably is sufficiently fluid to be coated onto a surface by dipping or spraying. When dried or cured on a surface, the photocatalytic composition should desirably form an abrasion-resistant, thermostable composition which is capable of adhering to the surface and of transmitting ultraviolet light to the photocatalyst contained therein. Upon complete oxidation, the binder should remain adhered to the surface as a transparent, non-volatile film. The photocatalyst composition, when dried or cured on a surface, absorbs ultraviolet (UV) light and reduces its flux at the underlying surface, preferably to less than 10% of the flux at the outer surface.

Binders

The binders of the present invention do not interfere with the chemical reactivity of the photocatalyst (including photooxidation and photoreduction reactions), but permit ready access of the reactants to the surface of the photocatalyst and transmit UV light. After drying or curing or extended use of the photocatalyst they are substantially non-oxidizable, that is, their polymeric backbones contain few, if any, oxidizable atoms. Because significant oxidation of the binder would render the material non-adherent to a substrate or reduce transmittance of UV-light reducing its flux at the catalyst, substantially oxidizable binder is not useful in the present invention. The preferred binders do contain oxidizable carbon and or hydrogen atoms, not in the backbone, but covalently bound to the backbone atoms. The amount of such covalently bound oxidizable carbon and/or hydrogen atoms in the binders is low, that is, less than about 20 weight percent, and most preferably less than

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about 15 weight percent. After weathering or prolonged UV exposure, the oxidizable carbon content of the binders is preferably less than about 15 weight percent and most preferably less than about 10 weight percent. In the most preferred binders, carbon dioxide will be evolved upon their oxidation. Upon exhaustive oxidation, the residual weight of the binder is at least about 70%, and preferably at least about 80%, of the initial weight of the binder.

The binder compositions dry or cure to form polymeric thermostable compositions, preferably having a weight average molecular weight of at least about 500 and polymeric backbones of about twelve or more bound atoms with no more than about one carbon atom in six in the backbone, and preferably no more than about one carbon atom in twelve.

In a preferred embodiment, the binders of the present invention are formed of porous alumina silica; silicone, or siloxane; or polymers or mixtures thereof. Boron oxide may be used, but is not preferred in applications in water due to the fact that it is slightly water soluble, producing boric acid. When aluminates or borates are used, acid may be added to cause their polymerization. Low molecular weight aluminates or borates in alkaline solutions may be polymerized by absorbing carbon dioxide from the atmosphere.

Porous alumina and silica, e.g., hydrated aluminum and silicon oxides, are commercially available e.g., under the trade name DISPAL, Vista Chemical. In contrast to the non-porous silica and alumina used by the paint industry to reduce or mask the photoactivity of the pigment particles, it has been surprisingly found that the binders of the present invention do not prevent photooxidation or photoreduction reactions. Small crystallites of silica or alumina (generally less than about 50 nm, preferably less than about 30 nm, and most preferably less than about 15 nm

diameter) in the fluid binder composition contain oxygen-bound hydrogen atoms. Upon drying and curing they lose water, forming bonds between the crystallites of alumina, silica, and photocatalyst particles. (脱水和結合)

5 Silicates, aluminates, and borates, and mixtures thereof, also are suitable non-oxidizable binders for the photocatalytic particles of the present invention. When dried or cured onto a substrate, polysilicates, polyaluminates, or polyborates are formed. In general, acid is used to initiate polymerization; however, low molecular weight aluminates or borates in alkaline solutions can be polymerized through absorption of CO₂ from the air.

15 Silicones, including siloxane, are commercially available and may be applied to a surface as a prepolymer, a non-crosslinked polymer, or as a crosslinked polymer. The terms silicone, siloxane, polysiloxane, and polysilicone are interchangeably used, and refer herein to compounds having multiple sequential bonds of alternating Si and O atoms, where a substantial fraction of the Si atoms are also bound to either carbon or hydrogen atoms or both. The carbon atoms can be of alkyl or of aryl groups. Examples of alkyl groups include methyl, trifluoromethyl and ethyl. Examples of aryl groups include phenyl and benzyl.

25 The term silane encompasses all non-polymeric compounds of the element Si having bonds between silicon and carbon atoms and/or hydrogen, halogen, or other atoms. Herein, silanes are compounds that can polymerize to form a silicone by forming multiple sequential bonds of alternating Si and O atoms. In addition, vinyl silanes undergo vinyl polymerization reactions to form polyvinyl silanes and hydrosilylation reactions, where vinyl groups polymerize by reacting with Si-bound H atoms. Epoxy (glycidyl) silanes may polymerize by reactions opening

their epoxy rings. A general discussion of silicones is found, for example in Kroschwitz, Concise Encyclopedia of Polymer Science and Engineering, 1990 Ed., page 1048.

5 Silanes (as defined above), silicone, siloxane,
polysiloxane, polysilicone, silanols (precursors, that upon
loss of water, form silicones or silica gel),
10 silsesquioxanes (polysiloxanes having multiple rings of
alternating silicon and oxygen atoms) and silica gels are
useful in the binder compositions of the present invention.
15 The preferred binder compositions are made with compounds
in which silicon atoms are covalently bound to alkyl
groups. These compounds are mixed with photocatalyst to
form a thermosetting composition. When applied to a
surface, the photocatalyst-binder composition dries or
cures to form a thermosettable, abrasion resistant
composition which adheres onto the surface.

Examples of useful polymeric precursors or prepolymers
include dihalosilanes, trihalosilanes, tetrahalosilanes,
alkyltrihalosilanes, dialkyldihalosilanes,
20 aryltrihalosilanes, diaryldihalosilanes, dialkoxysilanes,
trialkoxysilanes, tetraalkoxysilanes,
alkyltrialkoxysilanes, and dialkyldialkoxysilanes.
Examples include methyltrichlorosilane, (CH_3SiCl_3),
methyltrimethoxysilane ($\text{CH}_3\text{Si}(\text{OCH}_3)_3$), methyltriethoxysilane,
25 methyltripropoxysilane, and octyltriethoxysilane. These
polymer precursors react to form two-dimensional polymers
and three-dimensional crosslinked polymer networks.

Two dimensional silicone polymers include linear,
cyclomer, and ladder forms. Linear forms include, for
30 example, polydiethoxysiloxanes, poly-dimethoxysiloxanes;
cyclomers include polysilsesquioxanes, e.g., poly
(methylsilsesquioxane). Silsesquioxanes are polysiloxanes
having multiple rings consisting of alternating Si and O
atoms. A substantial fraction of the ring Si atoms is

bound to a C or H atom, which may be bound, for example, to a methyl or trifluoromethyl group.

Crosslinked polymers are formed, for example, when silicon atoms of different chains are linked through oxygen atoms, and may form from alkoxy group carrying silicones through loss of ethers; their partial reaction with water and loss of alcohol; or from halogen-containing silicones by their reaction with water or hydroxyl ions and loss of halide. Crosslinking also may occur through oxidation by air, O₂ or peroxide, or by a N and O containing molecule, such as a nitrogen oxide or a nitrite or nitrate, or by an ion containing an oxidized halogen such as chlorite or hypochlorite. A silica gel, which is a crosslinked network of Si-O-Si bonds, terminated by Si-OH bonds, can also be used. Because Si can bond to four neighboring O atoms, the extent of crosslinking can be high in silica gels. Hydration, i.e., the presence of Si-OH groups terminating chains or networks, provides an open, high surface area structure where Si-OH groups couple upon heating to form a more dense structure with more Si-O-Si groups, by loss of water. A continuum of structures of decreasing porosity exist between Si(OH)₄ and fused quartz, SiO₂.

Prior to crosslinking, silicones, including siloxanes are usually liquids or solids that melt and are soluble in organic solvents and are dispersible in water. Prepolymers are generally soluble in alcohol, water and their mixtures. Some examples of solvents for polymerizable alkoxysilanes are alcohols, such as methanol, ethanol, and isopropanol and ethylene glycol; ketones, such as acetone and methyl ethyl ketone; alkanes, such as hexane and octane; aromatics, such as toluene and xylene; and others including N-methylpyrrolidone, diethylsuccinate, ethylene glycol diacetate, tetrahydrofuran, dimethylformamide, dimethylsulfoxide, and methylene chloride. The amount of water may vary with the polymerizable compound, but in

general is about one-half to one mole of water per mole of alkoxy group on the polymer precursor. For example, analkyl trialkoxy silane precursor would require one and one half to three water per mole of precursor. In general, alcohol is used at five times the amount of water.

It is preferred to use solvents which generate limited volatile organic compounds (VOC's). In general, about 10% by weight of the binder is placed in solvent, although the amount of binder may vary from about 0.1% to about 75%. In determining the amount of binder and solvent, consideration is given to the thickness of the layer to be produced and the viscosity of the desired composition for dispersing the catalyst and the application method to a specific surface.

Siloxanes can be crosslinked by reactions catalyzed by known curing agents, including organo-titanium compounds such as titanium isopropoxide. Crosslinked, three-dimensional siloxane networks can be suspended or dispersed in solvents or water, but usually do not dissolve.

In the present invention, the binder composition may include a non-crosslinked or partially crosslinked siloxane. Upon drying and curing of the composition on a surface, the non-crosslinked or partially crosslinked binder is further crosslinked to form thermostable, adherent coatings on the surface.

Although the silicon-based binder compositions are low in oxidizable carbon, it is preferred that they not be free of carbon. The presence of alkyl or aryl functions, or both, attached to the silicone, e.g., polysiloxane or cyclomer backbone e.g., as terminating functions, is preferred, as alkyl or aryl derived polysiloxanes or cyclomers form hydrophobic, smooth, difficult to oxidize, thermostable and hard films that are transparent (clear to translucent). The hardness of these films can exceed 95 on the Rockwell M hardness scale and is generally in the range of 70 to 120. These are preferred binders when glossy,

hard coatings are sought, for example in photoreactively self-cleaning waxes for use on surfaces, e.g., of automobiles or ceramic tiles or in photoreactively self-cleaning automobile paints, overcoatings, or finishes.

5 In general, the toughest binders that are also the hardest and most abrasion resistant, are the alkyl silsesquioxanes, particularly if cured with an organotitanate. Polysiloxanes formed by polymerizing
10 alkyltrimethoxysilanes, particularly methyl trimethoxysilane under mildly acid conditions with about one mole of water added per alkoxy group in a dry solvent, such as alcohol, are softer, i.e., form tough, abrasion resistant, yet more plastic (deformable) coatings. Both
15 are clear. The methyl silsesquioxane coating, even without further crosslinking by titanate, can be heated to a high temperature, e.g., in excess of 400°C, without decomposition.

Coatings made by polymerization of hydrogen carrying silanes such as HSiCl_3 or $\text{HSi}(\text{OCH}_3)_3$, cure in air by
20 oxidation of the silicon-bound hydrogen atoms, loss of water and formation of Si-O-Si bonds.

Photocatalyst

Photocatalysts useful in the invention are generally photoactive transition metal oxides, including, but not
25 limited to TiO_2 , ZnO , CaTiO_3 , WO_3 , SnO_2 , MoO_3 , Fe_2O_3 , Nb_2O_5 , Ta_2O_5 , and $\text{Ti}_x(\text{Zr}_{1-x})\text{O}_2$, where X has a value of between 0 and 1. SiC is also a useful photocatalyst. Preferred are TiO_2 and ZnO . The photoactive
30 catalyst particles can be approximately between 1 and 100 nm in diameter, however, the photocatalytic properties of smaller particles are superior to those of the larger particles. The preferred photocatalyst particles are between about 1 and about 50 nm in diameter, consisting of approximately 1-10nm crystallites.

The preferred photocatalyst particles have a high surface area per gram, e.g., higher than $30\text{m}^2/\text{g}$, preferably above $50\text{m}^2/\text{g}$ and most preferably greater than about $100\text{m}^2/\text{g}$ as measured by the BET method. Today's best photocatalysts reach about $300\text{m}^2/\text{g}$. In contrast, the surface area per gram of TiO_2 pigments is about $1\text{-}10\text{m}^2/\text{g}$. The difference is in the much smaller particles and crystallites of the photocatalyst particles.

In one embodiment of the invention, the combination of small (1-50 nm) photocatalytic particles with larger non-photocatalytic particles (approximately 150 - 250 nm) makes a useful self-cleaning paint composition. The small particles serve both as photocatalyst and as a binder for adhering the larger, light scattering, particles and adhering the particles to a surface.

The photocatalyst is activated by photons the energy of which exceeds the band gap of the photocatalyst. The preferred catalysts are activated when illuminated by approximately 2 to 6 eV photons (about 220-500 nm wavelengths), and preferably about 3.0 to 5.2 eV photons (about 240-400 nm), at an irradiance of at least $0.1\text{ uW}/\text{cm}^2$ and generally not more than about $100\text{ mW}/\text{cm}^2$. Titanium dioxide is photoactive in both its anatase and rutile phases, and for its photocatalytic function photon energies of about 3.0 to 4.5 eV are preferred. When excited by light in wavelengths shorter than about 410 nm (rutile) or about 390 nm (anatase), TiO_2 catalyzes oxidation-reduction reactions. For ZnO the preferred photon energies are about 3.3 to 4.5 eV. For SnO_2 , $\text{Ti}_x(\text{Zr}_{1-x})\text{O}_2$, CaTiO_3 , higher energy photons of at least 3.5 eV energy are preferred. For WO_3 and Fe_2O_3 photon energies as low as 2.8 eV are useful. Ta_2O_5 requires high photon energies, in excess of 5 eV.

The photocatalyst may catalyze oxidation or reduction reactions which serve to degrade a contaminant to a less noxious compound. Examples include oxidation of organic

compounds such as formaldehyde or ethylene oxide and reduction of organic compounds such as carbon tetrachloride.

Co-catalyst

5 The rate of photocatalytic reactions may be increased, e.g. to accelerate the removal of high levels of contaminants, by the addition of co-catalysts. The photocatalytic compositions of the present invention may thus include as co-catalysts palladium, platinum, rhodium,
10 ruthenium, tungsten, molybdenum, gold, silver, or copper, their oxides or sulfides to increase the rate of photocatalytic activity. Cocatalysts are preferably added in amounts of 0.01-2 catalyst weight % and are preferably incorporated in the surface, not in the bulk of the
15 catalyst crystallites. See for example, Wang et al., 1992, J. Am. Chem. Soc. 114:5230-5234 and Kraeutler B. and Bard A.J., 1978, J. Am. Chem. Soc. 100:5985-5992.

Hydrophobic Enhancer

20 It has been surprisingly found that photocatalytic oxidation-reduction reactions catalyzed by photocatalytic pigments are enhanced in the presence of a hydrophobic, oxygen-permeable compound. For example, a photocatalyst binder composition containing a hydrophobic binder, such as siloxane, has enhanced photoactivity as compared with a
25 composition containing a non-hydrophobic binder. In addition, a hydrophobic overcoating applied to a photocatalyst coated surface enhances the activity of the photocatalyst in its oxidation of organic phase soluble compounds, that is, compounds more soluble in organic
30 solvents than in water. This enhanced activity is seen whether the photocatalyst is bound to a surface by conventional sintering methods or when the photocatalyst is

bound to a surface via the binder compositions of the claimed invention.

The hydrophobic binder or overcoating serves to increase the contact angle with water by at least about 20°, and preferably by about 40°, when the third phase present is air. In a preferred embodiment, the contact angle between the coated surface and water when the third phase is air is between about 90° and about 180°.

Furthermore, the hydrophobic binder is permeable to the organic reactant and to molecular oxygen. It is also permeable to the products of the photocatalyzed reaction, particularly to carbon dioxide and to water.

Examples of appropriate hydrophobic binders or overcoatings include silicone and silane-derived compounds discussed above.

The hydrophobic binders or coatings of the catalyst extract organic molecules from fluid, e.g., air or water, concentrating these organics on the coated surface. The organic molecules, as well as oxygen, can rapidly diffuse in the coating, resulting in enhanced reactant flux to the photocatalyst dispersed in or coated by a hydrophobic binder or coating resulting in faster photocatalytic reactions. Thus the silicone, siloxane and silane-derived binders, as well as the microporous alumina and silica binders, are permeable to the reactants, which are organic molecules and oxygen in photooxidation reactions and halogenated organics and water in photocatalytic dehalogenation reactions.

Producing the photocatalyst-binder composition

The fluid photocatalyst-binder composition generally contains at least about 10% by weight photocatalyst and generally at least about 10% by weight binder. The composition must contain sufficient photocatalyst to achieve the photocatalytic activity required, e.g.,

oxidation of organic compounds, and sufficient binder to permit good adherence of the needed amount of photocatalyst particles to a surface. Generally, the composition will contain between about 10 and 90 weight percent of the photocatalyst particles and between 10 and 90 weight percent of the binder. Additional components may be co-catalysts, curing agents, enhancers, light-scattering pigments, solvents, surface active agents, viscosity affecting agents, stabilizers, and pH-controlling buffers.

A solid powder or an aqueous suspension of photocatalyst is added to a dispersion or solution of binder in water or in the organic solvent, or the catalyst may be formed in-situ, in a dispersed form in water or in a solvent as a colloid, known as a sol, which may convert, by cross-linking of the particles, to a network, usually a gel. The consistency of the fluid binder composition must be such that the photocatalyst particles may be dispersed therein and the composition applied to a surface by a method of choice. For example, porous alumina or silica may be suspended in water, and photocatalyst particles added to the suspension. Prepolymeric silicones including siloxanes may be dispersed or dissolved in an organic solvent containing photocatalyst particles.

Photocatalyst-binder compositions are generally prepared by combining the photocatalyst, binder, and solvent together and dispersing the photocatalyst through the use of a mixer with a high shear impellor operated at speeds up to 10,000 rpm. If not used immediately, the preparation can be stored in a sealed container to prevent evaporative loss of the solvent. If stored for long periods of time, the photocatalyst may settle and will need to be redispersed.

Application of photocatalyst-binder compositions

The photocatalyst-binder compositions of the present invention are thermostable. They can be applied from as liquid or, by dry-spraying as a powder. They can be applied to a large variety of surfaces, including glass,
5 ceramic, metal, plastic, wood, painted surfaces, and the like. Application from the liquid composition may be by dip-coating, spraying, painting, or other methods known to apply liquid-dispersed materials onto a surface. Once applied to a surface, the composition is permitted to dry
10 and/or cure, preferably at ambient temperature, or may be heated to assist in the drying or curing process. Preferably, if heat is used, the temperature is less than about 500°C, more preferably less than about 400°C, and most preferably less than about 200°C. When applied by
15 dry-spraying or as a powder, heating, usually to the softening temperature of the binder that at this stage must be thermoplastic, is required.

In general, the photocatalyst-binder composition is applied to a surface and permitted to dry and/or cure under
20 conditions suitable to remove solvents and cause polymerization and/or crosslinking of the binder composition and adherence of the photocatalyst-binder composition to the surface. The specific conditions will vary with the specific binder composition and the solvents,
25 curing agents, and other components within the composition. For example, compositions containing alkylsilsesquioxanes, alumina, or silica may be dried at low temperature, e.g., approximately 15 to 40°C for about 1 to 4 hours. Compositions containing polymerizable precursors such as
30 methyltrimethoxysilane, may be cured at approximately 100 to 200°C for about 1 to 4 hours or at approximately 5 to 40°C for about 72 to 240 hours.

It is preferred to carry out polymerization and crosslinking reactions in stages, so as to avoid the
35 buildup of stress which may lead to cracking or peeling of

the applied photocatalyst-binder composition. Stress generally results from shrinkage of a film in the condensation polymerization reaction. It is therefore preferred to prepolymerize a polymer precursor to a material that is still able to plastically deform, i.e., undergo plastic deformation under stress rather than break. After the major dimensional change (shrinkage of the polymer) has taken place, either in the composition prior to application or after its application to a surface, further crosslinking can be used to obtain an increasingly tough, rigid, difficult to abrade coating. Thus, in the stages of curing, the binder progresses from being plastic and deformable to being increasingly rigid and hard, without cracking or peeling from the surface.

To obtain well separated polymerization and crosslinking stages, two or more differently reactive functional groups in the polymer precursor(s) can be used. The first group polymerizes to a non-crosslinked or less crosslinked prepolymer, to form a coating that easily deforms under stress. Subsequent crosslinking through another functional group or other groups produces a more rigid coating. For example, functional groups forming Si-O-Si bridges which further polymerize and crosslink at different rates include: Si-OH by loss of water; Si-H by air oxidation and loss of water; Si-Cl by reacting with water and loss of HCl and water; hydrogen; alkyl and aryl groups Si-OR by hydrolysis and loss of alcohol, where the rate depends on the function R; Si-OR by loss of ether, with the rate depending on R.

30

Methods of Use

The photocatalytic-binder compositions of the present invention can be used to produce photoactive surfaces for the removal of contaminants from a fluid, e.g., air, water, and the like or from surfaces coated with the composition.

Thus, they can be advantageously applied to interior and exterior surfaces of buildings, walls, roofs, cars, boats, airplanes, windows, lamps, fixtures, air handling systems and purifiers, kitchen appliances, ceramic tiles and
5 ultraviolet light emitting lamps, and air filtration units to render these surfaces virtually self-cleaning and to remove contaminants from a fluid stream such as air or water passing over the surface.

The compositions can be applied to form permanent
10 coatings, similar in their permanence to paints on painted surfaces. Alternatively, they may form semi-permanent coatings, similar in their semi-permanence to waxes on surfaces, e.g., on a car or flooring. For example, a
15 silicone-based wax can be mixed with a photocatalyst to form a self-cleaning wax, e.g., a wax on which organic contaminants are photocatalytically degraded. In this embodiment, the wax itself is the binder.

When continuously or periodically illuminated by sunlight or artificial light containing photons of the
20 earlier specified energy, that are near UV photons in the case of the preferred photocatalysts, the coated surfaces retain a clean appearance, require less cleaning and painting, prevent growth of microorganisms such as mold, mildew and pathogenic organisms, and strip organic
25 pollutants from a stream of air or water contacting the coated surface. The coated surface need not be exposed at all times to a light (UV) flux. However, the hydrophobic binder or overcoating is active at all times, extracting contaminants from water or air for later reactions when
30 exposed to light.

The photocatalyst-binder composition of this invention can be applied to a surface by methods generally known for applying fluid (pourable) compositions, e.g., by painting, spraying, dipping, or spin coating. When the composition
35 dries or cures on the surface, it forms an adherent,

abrasion-resistant, thermostable film. Organic compounds which contact the film are absorbed or retained by the film. When exposed to UV light, the film transmits a substantial portion of the incident UV light to activate the photocatalyst particles and induce reactions which degrade the contacting organic compounds.

In a preferred embodiment, the photocatalyst-binder composition is applied to the surface of a reactor bed. Air or water passing through the reactor contacts the composition and contaminants contained in the air or water are subjected to photocatalytic reactions in the bed. In a fluidized bed reactor, the buoyancy of the coated particles, e.g., spheres or particles having an approximately spherical shape, is adjusted to permit particle and fluid circulation and particle distribution within the reactor. Thus, when the fluid (e.g., air or water) flows upward, the spheres are pushed up and suspended by force of flushing fluid. When the particles are buoyant in the fluid, the fluid flows downward through the bed of particles and drag force of the fluid distributes the particles in the bed. For upward flow of water in the reactor, a coated sphere density of about 1-2 g/cm³ is useful. When water flows downward, for the spheres to be forced down, then rise due to their buoyancy, spheres of about 0.3-1.0 g/cm³ are useful. Fluidized bed reactors with upward flow of air are also useful in extraction and photocatalytic removal of impurities from air. In this case, low density coated bubbles having approximately 0.05 to 1.0 g/cm³ density are useful. At lower densities, the materials may be pulverized, and at higher densities they sink too fast.

In a most preferred embodiment, a photocatalyst-binder composition packed bed reactor is formed using wave-guiding glass spheres coated with the photocatalyst-binder composition as the packing of the reactor.

As shown in Figure 1, a wave-guiding photoreactor includes a packed bed of glass spheres 2, which are preferably and optionally coated with silicone, but only at points of contact 4 between the spheres. The packed bed 6
5 is formed within a conduit 8 which surrounds a source of ultraviolet light 10. Preferably, and optionally, a film of silicone 12 is positioned between the conduit 8 and the packed bed 6 such that the glass spheres which are immediately adjacent to the source of ultraviolet light 10
10 are intimately contacting the film of silicone 12. The glass spheres 2 are coated on all exposed surfaces, except at contact points 4 with other spheres or with the conduit 8, with the photocatalyst-binder composition of the present invention. The photoreactor also contains an inlet 14 and
15 an outlet 16 for passage of air or water to be treated.

The wave-guiding photoreactor described above provides a high surface area of the photocatalyst which is illuminated for photoreactions. The positioning of the packed glass spheres and the absence of photocatalyst-binder composition at the contact points provides maximum
20 light distribution within the reactor.

The above-described wave-guiding photoreactor housing a source of UV light may be produced by placing a sufficient quantity of glass or UV transmitting photostable
25 plastic spheres into a conduit to pack the conduit, so that the spheres optically contact one another and do not move freely within the conduit. The spheres may be heated to cause softening and adherence on cooling at contact points. In a preferred embodiment, the conduit is lined on its
30 inner surface with a layer of silicone into which the spheres immediately adjacent to the conduit are imbedded. Also in the preferred embodiment, clear, UV-transmitting silicone is present on the glass spheres only at points of contact between the spheres. This may be accomplished, for
35 example, by coating the beads with silicone prior to

packing the conduit. After packing the conduit with the silicone-coated spheres, a solvent is applied to the packed bed to rapidly strip the silicone on the exposed surfaces of the spheres but not from between the spheres. Such a solvent is isopropanol. After removal of exposed silicone, the packed spheres have residual silicone only at contact points between spheres. Alternatively, the reactor bed is produced by layering one row of spheres at a time applying an amount of silicone to the contact points prior to applying the next sphere layer.

The fluid photocatalyst-binder composition is then poured through the inlet into the packed spheres with the excess draining through the outlet and permitted to dry and/or cure on the exposed surface of the spheres. This process results in a packed bed reactor containing photocatalyst-binder coated glass spheres except at points of contact between the spheres. Such a configuration allows for maximal transmission of UV light through the glass beads at their contact points and maximum exposure and absorption of UV-light¹ by the photocatalyst in the reactor.

To achieve maximal wave-guiding of the UV light through the reactor, the index of refraction is approximately matched for the packing material, the contact material (silicone in the example described above) and the envelope of the UV lamp. Preferably, the index of refraction of the envelope of the lamp (I_L) is approximately equal to or smaller than the index of refraction of the contact material, i.e., silicone (I_s) which is approximately equal to or slightly greater than the index of refraction of the packing material (I_p).

The packed bed reactor of the present invention permits efficient transfer of UV light throughout the bed. UV light is transmitted through the contact points and is absorbed by the photocatalyst coating (see Fig. 2).

In an alternative embodiment, the photocatalyst-binder compositions of the present invention are used to form a biocidal surface. Exposure of the surface to UV light induces photocatalytic reactions the products of which kill and degrade micro-organisms which are in contact with the surface.

EXAMPLES

The following examples are designed to illustrate certain aspects of the present invention. The examples are not intended to be comprehensive of all features and all embodiments of the present invention, and should not be construed as limiting the claims presented herein.

EXAMPLE 1

© Poly(methylsilsesquioxane)-TiO₂ Composition

A photocatalyst-binder composition was prepared by mixing 27% by weight of poly(methylsilsesquioxane) also known as octakis(trimethylsiloxy)silsesquioxane (Gelest, Inc., Tullytown, PA); 6% by weight titanium dioxide (Degussa P-25, Degussa Corporation, Charlotte, NC); and 67% by weight isopropanol.

After mixing, the composition was applied to a borosilicate glass slide by dipping the slide into the composition mixture and draining off excess fluid. The coated slide was dried at ambient temperature (approximately 20°C) permitting the isopropanol to evaporate for approximately two hours. When dry, the composition on the slide was translucent, and could not be removed from the glass surface by rubbing, could not be pulled off by applied cellophane tape (the "tape test") and could not be washed off with water.

The above procedure was repeated using the components described in Table 1 below, and applying the compositions to the various surfaces as indicated in the Table. Each

resulted in a translucent coating which was not removed from the surface by rubbing, pulling with cellophane tape, or washing with water.

TABLE 1

SURFACE	CATALYST	BINDER	SOLVENT
BOROSILCATE GLASS	6% TiO_2	27% poly(methylsilsesquioxane)	67% isopropanol
SODA-LIME GLASS	6% TiO_2	27% poly(methylsilsesquioxane)	67% isopropanol
FUSED QUARTZ	6% TiO_2	27% poly(methylsilsesquioxane)	67% isopropanol
AIR OXIDIZED SILICON WAFER	6% TiO_2	27% poly(methylsilsesquioxane)	67% isopropanol
BOROSILICATE GLASS	3% TiO_2	28% poly(methylsilsesquioxane)	69% isopropanol
SODA LIME GLASS	3% TiO_2	28% poly(methylsilsesquioxane)	69% isopropanol
FUSED QUARTZ	3% TiO_2	28% poly(methylsilsesquioxane)	69% isopropanol

EXAMPLE 2

o Aluminum Oxide - TiO_2 Bound to Glass

A photocatalyst-binder composition was prepared by mixing 0.5% by weight aluminum oxide (Vista Dispall, Austin, TX), 0.5% by weight titanium dioxide (Degussa P-25), and 99% by weight water.

A borosilicate glass slide was coated with the mixture by spraying the surface of the glass with a pressurized stream of the mixture. Spray-coating was accomplished by

atomizing the binder-photocatalyst-solvent mixture using an atomizing spray nozzle (Spraying Systems, Wheaton, IL) pressured with nitrogen gas at 20 psi. The mixture flow rate was approximately 0.5 gallons per hour with a droplet size of approximately 30 microns. The coated slide was permitted to dry at ambient temperature (approximately 20°C) for approximately two hours.

The above procedure was repeated using the components described in Table 2 below, applying the compositions to the various surfaces as indicated in the Table. When dry, the coating on the slide was translucent, and could not be removed from the glass surface by pulling with applied cellophane tape (tape test).

TABLE 2

SURFACE	CATALYST	BINDER	SOLVENT
BOROSILICATE GLASS	0.5% TiO ₂	0.5% AlO	99% H ₂ O
SODA LIME GLASS	0.5% TiO ₂	0.5% AlO	99% H ₂ O
FUSED QUARTZ	0.5% TiO ₂	0.5% AlO	99% H ₂ O
AIR OXIDIZED SILICON WAFER	0.5% TiO ₂	0.5% AlO	99% H ₂ O

EXAMPLE 3

Photooxidation of Volatile Organic Compounds

A coated fused quartz substrate prepared as described for Example 1 (6% TiO₂; 27% poly(methylsilsesquioxane); 67% isopropanol) was tested for its ability to photooxidize volatile organic compounds by placing the coated substrate in a gas-tight glass vessel filled with air at atmospheric pressure. The vessel was provided with a 4.9cm² window through which UV light was passed to illuminate the

titania-coated substrate. The gas volume of the vessel was 49cm³. The size of the coated substrate was 4.9cm².

5 Toluene (10μl) was injected into the vessel through a septum port and allowed to vaporize. The initial toluene concentration was 1.9μmoles/cm³ of air. UV light (12.2mw/cm² at 365 nm) was then used to illuminate the photocatalyst-coated substrate. The concentration of toluene as a function of time was monitored by taking gas samples using a gas-tight syringe and measuring the amount of toluene by
10 gas chromatography with flame ionization detection. Table 3 shows the decrease in the amount of gaseous toluene as a function of time.

TABLE 3

TIME (HR)	TOLUENE CONCENTRATION (MOLES/CM ³)
0.0	1.90 X 10 ⁻⁶
0.5	1.43 X 10 ⁻⁶
1.0	1.22 X 10 ⁻⁶
1.5	1.07 X 10 ⁻⁶

15
20 The above experiment was repeated using a fused quartz substrate coated with the aluminum-oxide-TiO₂ composition prepared as described for Example 2 (0.5% TiO₂; 0.5% AlO; 99% water). Table 4 shows the decrease in the amount of gaseous toluene as a function of time.

TABLE 4

TIME (HR)	TOLUENE CONCENTRATION (MOLES/CM ³)
0.0	1.9×10^{-6}
0.5	3.0×10^{-7}
1.0	1.9×10^{-7}

UV = 2.6 mW/sq. cm

EXAMPLE 4

10 Application of a hydrophobic coating to a hydrophilic photocatalytic surface

15 The photocatalytic coating in Example 2 was made hydrophobic by spraying onto the surface of the coating one of the following solutions: 0.1% Glassclad 6C (United Chemical Technologies) in isopropanol or 0.1% Glassclad 18 (United Chemical Technologies) in water. Glassclad 6C is a chlorine-terminated poly(dimethylsiloxane) and Glassclad 20 18 is a hydroxyl-terminated poly(dimethylsiloxane). Soda-lime glass was the substrate material for the photocatalytic coating. An atomizing sprayer with nitrogen or carbon dioxide as propellant gas was used. Liquid droplets large enough to be visible were not allowed to form on the surface. Spraying continued until transmission FTIR of the glass and coating revealed a peak at approximately 3000cm^{-1} with an absorbance of 0.05, 25 indicating the presence of Glassclad on the surface of the photocatalytic coating.

EXAMPLE 5

Photooxidation of toluene on a hydrophobic photoactive coating

The photooxidation of toluene by the coating from Example 2, made hydrophobic with glassclad 6C using the procedure in Example 3, was tested by placing the coated hydrophobic substrate of Example 3 (fused quartz) in a gas-tight glass vessel filled with air at atmospheric pressure. The gas-tight vessel had a 4.9cm^2 window through which UV light could pass and illuminate the photocatalyst-coated substrate. The gas volume of the vessel was 49cm^3 .

Toluene ($10\mu\text{L}$) was injected into the vessel through a septum port and allowed to vaporize. The initial toluene concentration was $1.9\mu\text{moles}/\text{cm}^3$ of air. UV light ($2.6\text{mW}/\text{cm}^2$ at 365nm) was then used to illuminate the titania coated substrate. The concentration of toluene as a function of time was monitored by taking gas samples using a gas-tight syringe and measuring the amount of toluene using gas chromatography with flame ionization detection. Table 5 shows the decrease in the amount of gaseous toluene as a function of time. Within the first 30 minutes, the concentration of toluene was decreased to a level below that seen without the hydrophobic overcoating in 1.5 hours.

TABLE 5

TIME (HR)	TOLUENE CONCENTRATION (MOLES/ CM^3)
0.0	1.90×10^{-6}
0.5	2.60×10^{-7}
1.0	1.50×10^{-7}

EXAMPLE 6Photodegradation of carbon tetrachloride (CCl_4)

The ability of the coating from Example 2 to photodegrade gas-phase CCl_4 was tested by coating a calcium fluoride infrared crystal with the photocatalyst-binder

composition as described for Example 2. The coated substrate (CaF_2) was placed in a gas-tight glass vessel filled with air at atmospheric pressure. The gas-tight vessel had a 4.9cm^2 window through which UV light could pass and illuminate the titania-coated substrate. The gas volume of the vessel was 49cm^3 . CCl_4 ($10\mu\text{L}$) was injected into the vessel through a septum port and allow to vaporize. The initial CCl_4 concentration was $1.15\mu\text{moles}/\text{cm}^3$ of air. UV light ($6\text{mW}/\text{cm}^2$ at 365nm) was then used to illuminate the titania coated substrate for 24 hours. After the 24 hour period had elapsed, the cell was removed from the UV light and placed in an infrared spectrophotometer to measure the amount of carbon dioxide (CO_2) generated from the degradation of CCl_4 . After 24 hours of UV illumination, approximately 4.6×10^{-7} moles of CCl_4 was converted to CO_2 .

EXAMPLE 7

Surface Cleaning Capability

A sample of soda-lime glass coated with a hydrated aluminum oxide- TiO_2 composition was prepared as described for Example 2 (0.5% TiO_2 ; 0.5% hydrated aluminum oxide; 99% water).

The surface cleaning ability of the coated substrate was tested by placing $10\mu\text{l}$ of a 1% solution of stearic acid in isopropanol on the surface of the film coating and exposing it to UV light ($4\text{mW}/\text{cm}^2$ at 365 nm) by front illumination, i.e., coated side. The amount of stearic acid on the glass was monitored by transmission infrared spectroscopy through soda-lime glass.

Stearic acid showed a major absorption peak at 2930 cm^{-1} attributed to C-H stretching vibrations. The integrated area of this peak was related through calibration to the amount of stearic acid applied, then used to measure

photoreactive removal of organic matter from the surface as a function of time.

5 The amount of stearic acid remaining on the surface after exposure was calculated from the integrated areas of the peaks at or near 2930cm^{-1} using the percentage of the area prior to UV illumination. Table 6 shows the change in stearic acid concentration as a function of time.

TABLE 6

ILLUMINATION TIME (HR)	SURFACE CONCENTRATION OF STEARIC ACID (MOLE/CM ²)
0.0	4.22×10^{-7}
0.5	4.08×10^{-7}
1.0	3.92×10^{-7}
1.5	3.77×10^{-7}
2.0	3.61×10^{-7}
2.5	3.45×10^{-7}
3.0	3.34×10^{-7}

There was no change when the samples were kept in the dark for 48 hours.

20 This study was repeated as described above, except that the film was back-illuminated, i.e., through the uncoated side of the substrate. Table 7 shows the change in the ratio of residual to initial amounts of stearic acid on the surface as a function of time.

TABLE 7

TIME(HR)	FRACTION OF INITIAL CONCENTRATION
0	1.00
2	0.7
3.5	0.6

5 This study was further repeated, using the following photocatalyst-binder composition applied to the soda-lime glass substrate: 3%TiO₂; 28% poly(methylsilsesquioxane); 69% isopropanol. The sample was front illuminated. The change
10 in ratio of residual to initial amounts of stearic acid as a function of time are shown in Table 8

The study was repeated using 6%TiO₂; 27% poly(methylsilsesquioxane) and 67% isopropanol. Figure 8
15 shows the change in the ratio of stearic acid remaining as a function of time.

TABLE 8

TIME(HR)	FRACTION OF INITIAL CONCENTRATION
0	1.00
2	0.65
5	0.58
72	0.55

20 This study was further repeated using 10% TiO₂, 20% methyltrimethoxysilane, 61.2% isopropanol, 8.1% water, and 0.7% 3N HCl. Table 9 shows the change in stearic acid
25 concentration as a function of time.

TABLE 9

TIME (HR)	SURFACE CONCENTRATION OF STEARIC ACID
0	4.22×10^{-7}
1	3.55×10^{-7}
2	3.27×10^{-7}
3	3.01×10^{-7}
4	2.64×10^{-7}

EXAMPLE 8

6 Photooxidative Surface Cleaning with a SnO₂-containing film

10 The surface cleaning ability of a coating of tin oxide
on glass was tested by placing 100 μ L of a 1% solution of
stearic acid in isopropanol on the surface of the coating
and exposing it to UV light (1mW/cm² at 254nm) by front
illumination. Tin oxide-coated glass was prepared by spin-
15 coating at 2000 rpm colloidal tin oxide (18% in water, Alfa
Johnson Matthey, Ward Hill, MA) on a soda-lime glass
substrate and drying the coated-substrate for one hour at
100°C. The amount of stearic acid on the surface was
monitored by transmission infrared spectroscopy through the
20 soda-lime glass. At 2930cm⁻¹, stearic acid shows a strong
absorption peak resulting from C-H stretch. The absorbance
peak was integrated and the percentage of the area prior to
UV illumination was used to calculate the amount of stearic
25 acid remaining on the surface. Table 9 shows the change in
stearic acid concentration as a function of time for front
illumination.

TABLE 9

ILLUMINATION TIME (HR)	SURFACE CONCENTRATION OF STEARIC ACID (MOLE/CM ²)
0.0	9.10×10^{-8}
17.5	0.71×10^{-8}

5

EXAMPLE 9Application to Metal

A photocatalyst-binder composition was prepared as described for Example 1, using 6%TiO₂; 27% poly(methylsilosesquioxane); 67% isopropanol. After
10 mixing, the composition was applied by brush painting as an overcoating onto the driver's side of the hood and roof of a white automobile and allowed to dry at ambient temperature. As a control, an identical composition containing the binder, poly(methylsilsesquioxane), but no
15 TiO₂ photocatalyst, was similarly applied to the passenger side.

The isopropanol was permitted to evaporate under ambient conditions, (approximately 29±4°C). The resultant coating was translucent and could not be removed from the
20 auto's surface by rubbing, pulling with cellophane tape, or washing with water. the coating retained its adhesion, integrity, and remained colorless during two months of outdoor weathering in ambient sunlight, rain, freezing temperatures, wind, and driving. The driver's side
25 overcoated with the TiO₂-binder composition was consistently cleaner than the passenger side, and was essentially stain, grime, and soot free.

EXAMPLE 10Ultraviolet transparency of poly(methylsilsesquioxane)

The transparency of a 100 μ m film of poly(methylsilsesquioxane) on quartz was determined by measuring the absorbance of the film using a UV/Vis spectrophotometer. The quartz substrate was spray-coated with a solution of polymethyl silsesquioxane and isopropanol. Table 10 shows the percent transmittance at two different wavelengths. Transmittance of quartz is approximately 90%.

TABLE 10

WAVELENGTH (nm)	ABSORBANCE	% TRANSMITTANCE
250	0.38	42
370	0.42	38

EXAMPLE 11

Ultraviolet transparency of polymerized film of methyltrimethoxysilane

The transparency of a 100 μ m film of polymerized methyltrimethoxysilane on quartz was determined by measuring the absorbance of the film using a UV/Vis spectrophotometer. Table 11 shows the percent transmittance of two different wavelengths.

TABLE 11

WAVELENGTH (nm)	ABSORBANCE	% TRANSMITTANCE
250	0.14	72
370	0.11	78

EXAMPLE 12

Photodeposition of Platinum on Colloidal Tin Oxide

Platinum was deposited on tin oxide photoelectrochemically. H_2PtCl_6 (Aldrich Chemical, St. Louis, MO) (0.8mL) was dissolved in 80mL of deionized water. One mL of glacial acetic acid (Aldrich Chemical) was added as a hole scavenger. The pH of the mixture was adjusted to 4 by the addition of 0.5mL of 2M Na_2CO_3 (Aldrich Chemical) in deionized water. Colloidal SnO_2 (Alfa Johnson Matthey, Ward Hill, MA) (0.26g) was then added to the solution and the mixture was illuminated for 0.5 hours with 254nm light at approximately $2.3\text{mW}/\text{cm}^2$ while stirring. The temperature of the plating solution was maintained at 43°C and continuously purged with N_2 . Following the deposition, the solution was dialyzed with a 500 molecular weight cutoff dialysis membrane to remove excess platinumic acid. The tin oxide was kept in colloidal form. The amount of Pt photodeposited on the semiconductor surface was approximately 0.1% by weight.

EXAMPLE 13

Enhancement of the Rate of Stearic Acid Photooxidation on Tin Oxide by Platinum Modification

The photoactivity of nanocrystalline tin oxide (Alfa Johnson Matthey) and of the Pt-modified nanocrystalline tin oxide prepared as described in Example 11 was determined by measuring the photooxidation rate of stearic acid films on a nanocrystalline SnO_2 coated substrate. The coated substrates (soda lime glass or quartz) were prepared by spin coating colloidal SnO_2 or Pt-modified colloidal SnO_2 onto the substrate at 2000rpm. The SnO_2 or Pt-modified SnO_2 coverage was approximately $0.3\text{mg}/\text{cm}^2$. After spin coating, the substrates were dried at 100°C for one hour. After the coated substrate had dried and cooled, $100\mu\text{L}$ of 0.5% stearic acid in isopropanol was deposited on the SnO_2 or Pt-modified SnO_2 -coated surface. After the solvent evaporated, transmission infrared spectroscopy (i.e., through the SnO_2 -

coated substrate) between 3000cm^{-1} and 2900cm^{-1} was used to determine the initial amount of stearic acid on the surface. The peaks resulting from the C-H stretch in this region were integrated. The stearic acid coverage on the

5 SnO_2 or Pt-SnO_2 coated surface was approximately 4.6×10^{-7} moles/ cm^2 . Fourier transform infrared spectroscopy was performed on a Nicolet Magna-IR :Spectrophotometer Model 750 FTIR with a KBr beam splitter and MCT detector. Averaging was performed over 50 scans with a nominal

10 resolution of 4 cm^{-1} . The surfaces were then front illuminated with 254nm ultraviolet light at approximately $2.3\text{mW}/\text{cm}^2$. The illuminated surface area was 10.2cm^2 . After the illumination period, infrared spectroscopy was again used to determine the amount of stearic acid remaining on

15 the surface. The fraction of the initial stearic acid concentration remaining on the surface is shown in Table 12 as a function of illumination time.

TABLE 12

20

Time (min)	C/C ₀ Pt-SnO ₂	C/C ₀ SnO ₂
0	1.00	1.00
200	0.45	0.80
780	0.16	0.59
2600	0.003	0.43

EXAMPLE 14

25 Measuring Abrasion Resistance by the
Scratch Hardness Test

The pencil hardness test as described in: Paint and Surface Coating: Theory and Practice, R. Lamborne, ed, 1987, John Wiley & Sons, NY, pages 674-675 was used to

30 determine the abrasion resistance of several photocatalyst

compositions coated onto surfaces. The coated surfaces were prepared as described below.

1. A titanium dioxide-containing photoactive surface was prepared by coating soda-line glass with a solution
5 containing 99% wt water, 0.5% wt aluminum oxide (Vista Dispal), and 0.5% wt titanium dioxide (Degussa P-25). The solution was sprayed onto the glass as described for Example 1; applied to the glass by each of three coating methods: spin coated onto glass at 2000RPM for about one
10 minute; and dip coating, allowing excess solution to drain. In each case, water was allowed to evaporate under ambient conditions leaving behind a translucent coating.

2. A titanium dioxide-containing photoactive surface was prepared by coating soda-lime glass by the three
15 methods described above with a solution containing 99% wt water, 0.5% wt colloidal silica (Alfa Johnson Matthey), and 0.5% wt titanium dioxide (Degussa P-25). Water was allowed to evaporate under ambient conditions, leaving behind a translucent coating.

20 3. A titanium dioxide¹-containing photoactive surface was prepared by coating soda-lime glass by the three methods described above with a solution containing 67% wt isopropanol, 27% wt poly(methylsilsesquioxane), and 6% wt titanium dioxide (Degussa P-25). Isopropanol was allowed
25 to evaporate under ambient conditions, leaving behind a translucent coating.

4. A titanium dioxide-containing photoactive surface was prepared by coating soda-lime glass according to the following procedure: A solution of 50g
30 methyltrimethoxysilane, 13.3g water, and 100g of isopropanol was mixed well and 0.1g of 3N HCl was added while rapidly mixing. The mixture was allowed to partially polymerize for 24 hours at 25°C, forming a sol. To this sol, 16.3g of titanium dioxide (Degussa P-25) was added and
35 dispersed into the sol by rapid mixing. The titania-sol

mixture was then coated on soda-lime glass by spincoating at 2000RPM for about one minute. Samples of the coated glass were allowed to cure at 100°C for 4 hours or at 25°C for 72 hours. After curing, the coated slides were then
5 soaked in 10% HCl for 24 hours, rinsed with water, and dried at ambient temperatures.

The scratch-hardness test was applied to each sample of coated glass described above by pushing pencil lead firmly along the surface of the film at about a 45° angle
10 to the surface. The abrasion-resistance value for each coating was the maximum carbon hardness value, e.g., the highest number of pencil carbon which did not damage or break the coating. Using pencil leads No. 1 through No. 3, each of the coatings described above had a scratch-hardness
15 value of at least 2. Those coatings using the titania-sol mixture had a higher scratch-hardness value, withstanding a No. 3 pencil. The No. 3 pencil was the hardest used, thus the abrasion resistance of the titania-sol mixture was at least 3.

WE CLAIM:

- 1 1. A composition comprising:
2 particles of a photocatalyst responsive to
3 ultraviolet light; and
4 a binder for adhering said particles to a
5 surface, the particles dispersed throughout said binder,
6 the binder substantially non-oxidizable,
7 wherein the composition forms an abrasion-
8 resistant, thermostable film, said film adherent to
9 surfaces and the binder transmitting a substantial
10 proportion of incident ultraviolet light to activate the
11 photocatalyst particles to produce cleaning effects.

- 1 2. The composition of claim 1, wherein said binder
2 is a polymer precursor, a non-crosslinked polymer, or a
3 partially crosslinked polymer prior to its curing.

- 1 3. The composition of claim 1, wherein said binder
2 cures at a temperature less than approximately 85°F. → 30°C

- 1 4. The composition of claim 3, wherein said binder
2 cures at ambient temperature.

- 1 5. The composition of claim 1, wherein said binder
2 is selected from the group consisting of hydrated alumina,
3 silica, tin dioxide and mixtures thereof.

- 1 6. The composition of claim 1, wherein said binder
2 is a silicone.

- 1 7. The composition of claim 6 wherein said binder is
2 a cyclomer or a ladder polymer.

1 8. The composition of claim 6 wherein said binder
2 includes a silicon atom bound to a terminating group
3 comprising H, alkyl group, or aryl group.

1 9. The composition of claim 1 further comprising a
2 curing agent.

1 10. A curable composition comprising:

2 (a) ultraviolet light-absorbing photocatalyst
3 particles having a surface area of at least about 30 m²/g;
4 and

5 (b) a binder having a low oxidizable carbon
6 content, wherein the particles of the photocatalyst are
7 dispersed in the binder.

1 11. The composition of claim 10 wherein the surface
2 area is at least about 100 m²/g.

1 12. The composition of claim 10, wherein the
2 composition is curable upon drying at ambient temperature
3 or by the application of heat, radiation, or curing agent.

1 13. The composition of claim 12, wherein the
2 composition is curable at ambient temperature.

1 14. The composition of claim 1, wherein said binder,
2 at a thickness of approximately one micron, absorbs less
3 than about 50% of near ultraviolet photons of about 2.5 to
4 about 5.5 eV energy.

1 15. The composition of claim 14, wherein said binder
2 absorbs less than about 50% of the photons with energy in
3 the range of 2.5-4.0 eV.

1 16. The composition of claim 15, wherein said binder
2 absorbs less than about 10% of the photons having energies
3 near 3.5 eV.

1 17. A composition comprising:
2 particles of a photocatalyst responsive to
3 ultraviolet light; and
4 a binder for adhering said particles to a
5 surface, the particles dispersed throughout said binder,
6 the binder being substantially non-oxidizable; and
7 a film-forming hydrophobic composition selected
8 from hydrophobic compositions that are permeable to organic
9 molecules and to molecular oxygen,
10 wherein the composition dries to form an
11 abrasion-resistant, thermostable film, said film adherent
12 to surfaces and the binder transmitting a substantial
13 proportion of incident ultraviolet light to activate the
14 photocatalyst particles to produce cleaning effects.

1 18. The composition of claim 17, wherein the
2 hydrophobic composition comprises a silicone.

1 19. A composite comprising:
2 a first layer comprising particles of a
3 photocatalyst responsive to ultraviolet light; and
4 a second, hydrophobic layer comprising
5 a hydrophobic compound that is permeable to organic
6 molecules and to molecular oxygen.

1 20. The composite of claim 19, wherein said
2 hydrophobic compound comprises a silicone.

1 21. The composite of claim 19, wherein said
2 photocatalyst particles are dispersed in a substantially
3 non-oxidizable binder.

1 22. The composite of claim 21 wherein said non-
2 oxidizable binder comprises a hydrophobic compound that is
3 permeable to organic molecules and to molecular oxygen.

1 23. The composite of claim 22 wherein said
2 hydrophobic compound is a silicone.

1 24. The composition of claim 1, further comprising a
2 cocatalyst doped onto the photocatalyst.

1 25. The composition of claim 24, wherein said
2 cocatalyst is selected from the group consisting of
3 palladium, platinum, rhodium, ruthenium, tungsten,
4 molybdenum, gold, silver, copper, and oxides or sulfides
5 thereof.

1 26. The composition of claim 1, wherein said
2 photocatalyst catalyzes oxidation of organic compounds by
3 air or oxygen.

1 27. The composition of claim 1, wherein said
2 photocatalyst catalyzes dehalogenation in the presence of
3 water.

1 28. The composition of claim 1, wherein said
2 photocatalyst is selected from the group consisting of TiO_2 ,
3 ZnO , CaTiO_3 , SnO_2 , MoO_3 , Fe_2O_3 , WO_3 , Nb_2O_5 , SiC , and $\text{Ti}_x(\text{Zr}_{1-x})\text{O}_2$, where x has a value between 0 and 1.

1 29. The composition of claim 28, wherein said
2 photocatalyst is TiO_2 , ZnO , SnO_2 or a mixture thereof.

1 30. The composition of claim 1, wherein said
2 composition, when applied to a surface and dried or cured,

3 transmits no more than about 10% of incident ultraviolet
4 light to the underlying surface.

1 31. A method for removing organic compounds from air
2 or water comprising the steps of:
3 coating a surface with a composition comprising
4 particles of a photocatalyst responsive to ultraviolet
5 light and a binder for adhering said particles to a
6 surface, the particles dispersed throughout said binder,
7 the binder being substantially non-oxidizable,
8 wherein the composition dries or cures to form an
9 abrasion-resistant, thermostable film, said film adherent
10 to the surface and transmitting a substantial proportion of
11 incident ultraviolet light to activate the photocatalyst
12 particles to produce cleaning effects;
13 causing fluid having organic compounds therein to
14 contact the coated surface; and
15 exposing the contacted-coated surface with
16 ultraviolet light for a period of time sufficient to
17 degrade the retained organic compounds by a photocatalyzed
18 chemical reaction.

1 32. The method of claim 31 wherein said curing or
2 drying is at ambient temperature.

1 33. A method for manufacturing a self-cleaning
2 surface comprising the steps of:
3 a) applying onto a substrate a pourable
4 composition comprising:
5 (i) particles of an ultraviolet light-
6 absorbing photocatalyst; and
7 (ii) a binder having a low oxidizable carbon
8 content, wherein the particles of the photocatalyst are
9 dispersed in the binder; and

10 b) curing the applied composition to cause the
11 composition to adhere to the substrate.

1 34. The method of claim 33, wherein said curing is at
2 ambient temperature.

1 35. The method of claim 33, wherein the binder
2 comprises a hydrophobic compound.

1 36. The method of claim 33, further comprising, prior
2 to step (b);
3 applying a hydrophobic coating over the pourable
4 composition.

1 37. The method of claim 35, wherein the hydrophobic
2 coating comprises a silicone.

1 38. A self-cleaning surface comprising:
2 a substrate; and
3 a cured composition derived from
4 (i) particles of an ultraviolet light-
5 absorbing photocatalyst; and
6 (ii) a binder having a low oxidizable carbon
7 content, wherein said particles of photocatalyst are
8 dispersed in the binder and wherein said binder cures at
9 ambient temperature.

1 39. A photoreactive surface for removing organic
2 compounds from air or water comprising:
3 a substrate; and
4 a coating composition adhered to surfaces of the
5 substrate, the coating comprising:
6 (i) particles of a photocatalyst responsive
7 to ultraviolet light; and

8 (ii) a substantially non-oxidizable binder.

1 40. The photoreactive surface of claim 38, wherein
2 said binder cures at ambient temperature.

1 41. A biocidal surface comprising:
2 a substrate; and
3 a coating composition adhered to the substrate,
4 the coating comprising:
5 (i) particles of a photocatalyst responsive
6 to ultraviolet light; and
7 (ii) a substantially non-oxidizable binder
8 which cures at ambient temperature;
9 wherein exposure of the coated substrate to
10 ultraviolet light induces killing of microorganisms which
11 contact said coated substrate.

1 42. A fluidized bed reactor comprising:
2 substrate particles having an approximate
3 spherical shape, the approximate spheres suspended in fluid
4 and substantially coated except at points of contact, with
5 a photocatalytic composition, the composition comprising:
6 particles of a photocatalyst responsive to
7 ultraviolet light; and
8 a binder for adhering said particles to the
9 approximate spheres, the photocatalyst particles being
10 dispersed throughout said binder, and the binder being
11 substantially non-oxidizable,
12 wherein the composition forms an abrasion-
13 resistant, thermostable film adherent to the approximate
14 spheres and the binder transmitting a substantial
15 proportion of incident ultraviolet light to activate the
16 photocatalyst particles.

1 43. A packed bed reactor comprising:
2 substrate particles having an approximate
3 spherical shape, the approximate spheres packed within a
4 conduit and the spheres coated on approximately all
5 surfaces except at points of contact with a photocatalytic
6 composition comprising particles of a photocatalyst
7 responsive to ultraviolet light and a binder for adhering
8 said photocatalyst particles to the approximate spheres,
9 the photocatalytic particles dispersed throughout said
10 binder and the binder being substantially non-oxidizable,
11 wherein the composition forms an abrasion-
12 resistant, thermostable film, said film adherent to the
13 approximate spheres and the binder transmitting a
14 substantial proportion of incident ultraviolet light to
15 activate the photocatalyst particles.

1 44. The packed bed reactor of claim 40, wherein said
2 points of contact are coated with silicone.

FIG. 1

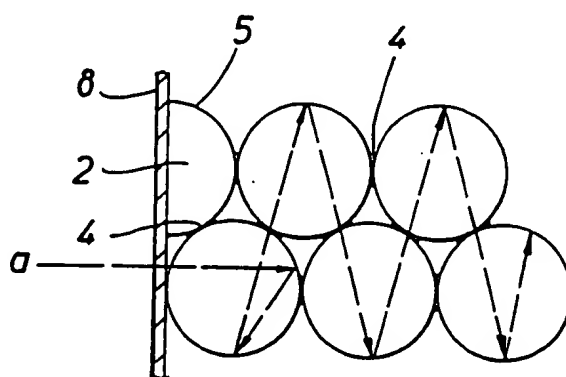
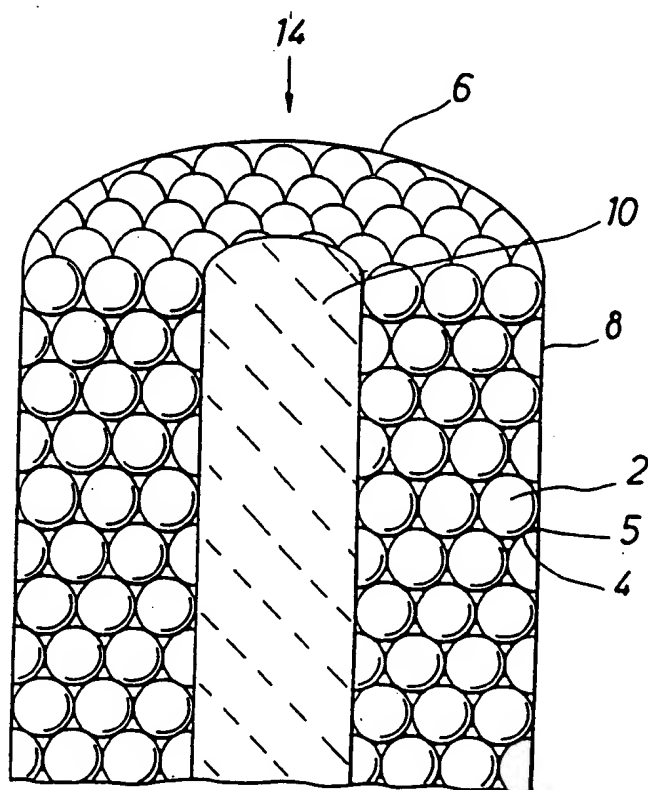


FIG. 2

1 / 1

SUBSTITUTE SHEET (RULE 26)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/12185

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) : B01J 21/06, 23/06

US CL : Please See Extra Sheet.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 502/242, 250; 106/437, 442, 445; 427/376.12, 387, 553; 134/1, 4.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

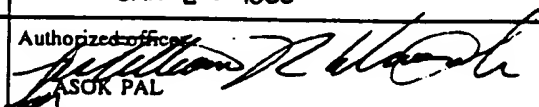
APS: search terms: photocatalyst? or photocatalysis, silicone, titanium(W)dioxide, zinc(W)oxide, biocidal.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US, A, 3,451,833 (BONITZ ET AL.) 24 June 1969, columns 1-4	1-41
Y	US, A, 4,209,432 (ROTH) 24 June 1980, Columns 1-4	1-41
Y	US, A, 4,544,470 (HETRICK) 01 October 1985, Figure 3 and associated description.	1-41
Y	US, A, 4,810,305 (BRAUN ET AL.) 07 March 1989; Columns 1-5	1-44
Y	US, A, 4,892,712 (ROBERTSON ET AL.) 09 January 1990, Figure 1 and associated descriptions	10-44

☒ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

Special categories of cited documents:		"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search 12 JANUARY 1995	Date of mailing of the international search report JAN 26 1995
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. NOT APPLICABLE	Authorized officer  ASOK PAL Telephone No. (703) 308-3809

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US94/12185

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,954,465 (KAWASHIMA ET AL.) 04 September 1990, Figures 1-3 and associated descriptions	42-44
X	US, A, 4,997,576 (HELLER ET AL.) 05 March 1991, Figure 3	1-41
Y	US, A, 5,164,003 (BOSCO ET AL.) 17 November 1992, Columns 1-4	1-41

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US94/12185

A. CLASSIFICATION OF SUBJECT MATTER:
US CL :

502/242, 250; 106/437, 442, 445; 427/376.12, 387, 553; 134/1, 4.